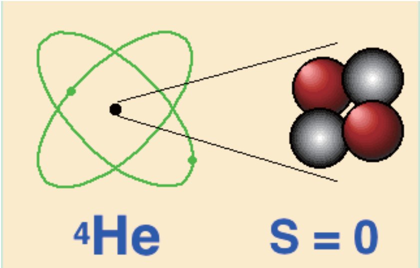
§3 Lambda Transition in Liquid Helium-4 and Two-Fluid Model

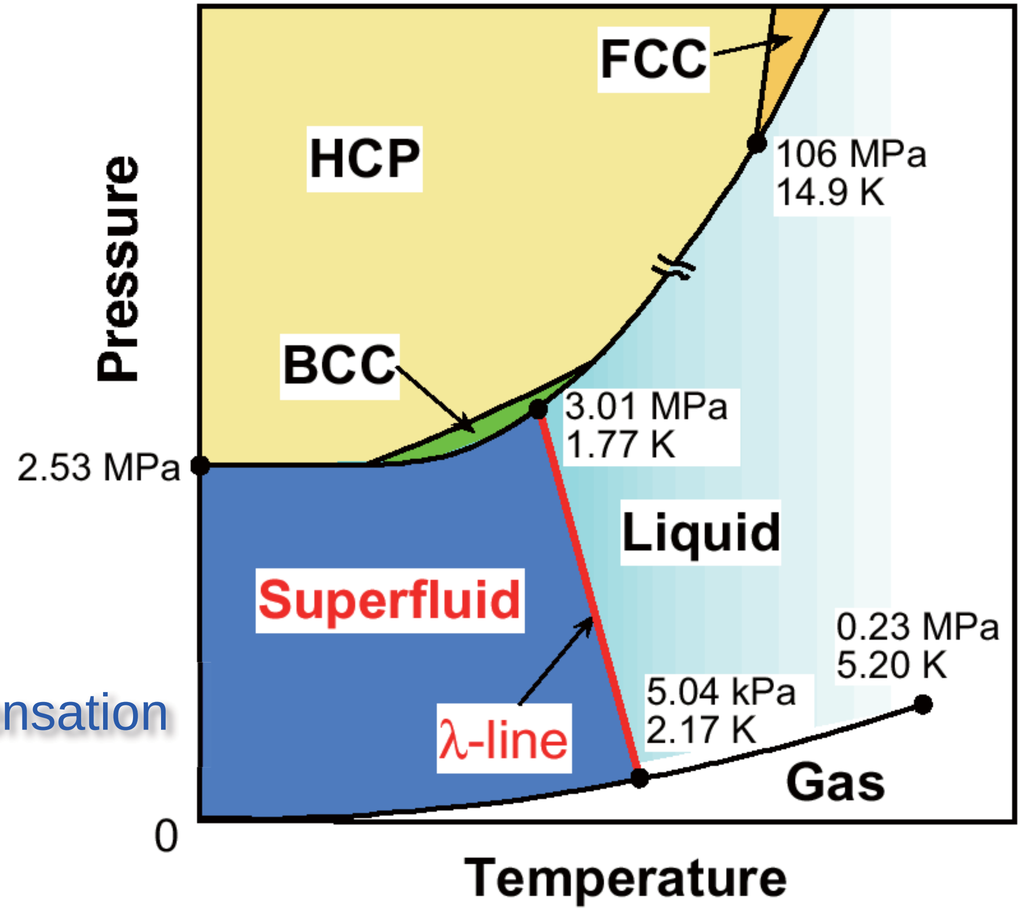
Phase diagram of ^{4}He



- composite **boson**
- second most common element in universe

- most **pure** and **simple** condensed matter
- large **quantum effects** (zero-point energy)
- **superfluidity** ($T < T_\lambda$)

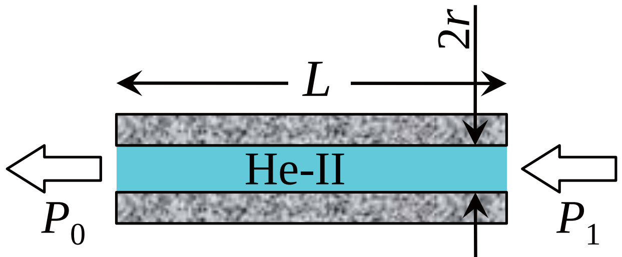
Bose-Einstein condensation



Various viscosity measurements of superfluid ^{4}He

1. Capillary flow experiment

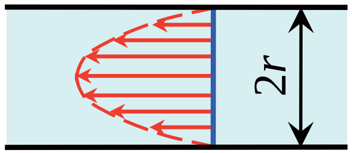
K.R. Atkins, Philos. Mag. Supp. **1**, 169 (1952)

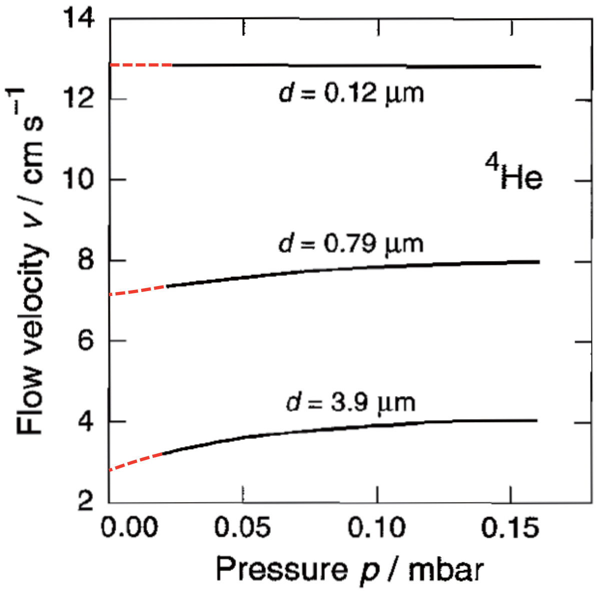


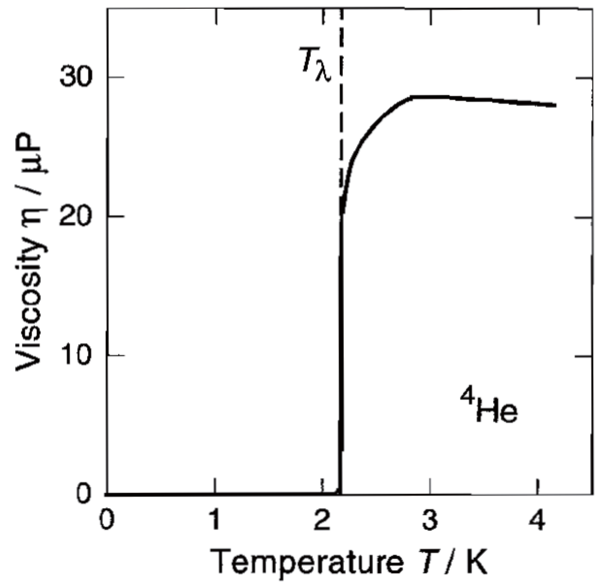
$P_1 - P_0 = \Delta P$

flow velocity: $v = \dfrac{\dot{V}}{\pi r^2} = \dfrac{r^2 \Delta P}{8 L \eta}$

(Hagen-Poiseuille law)





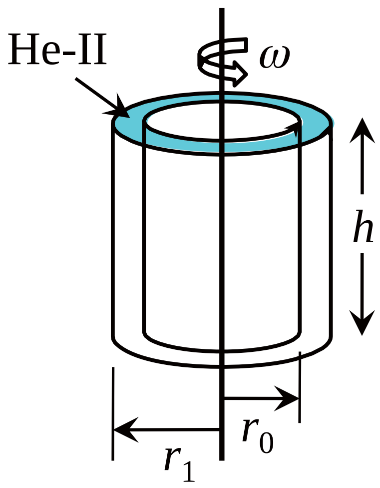


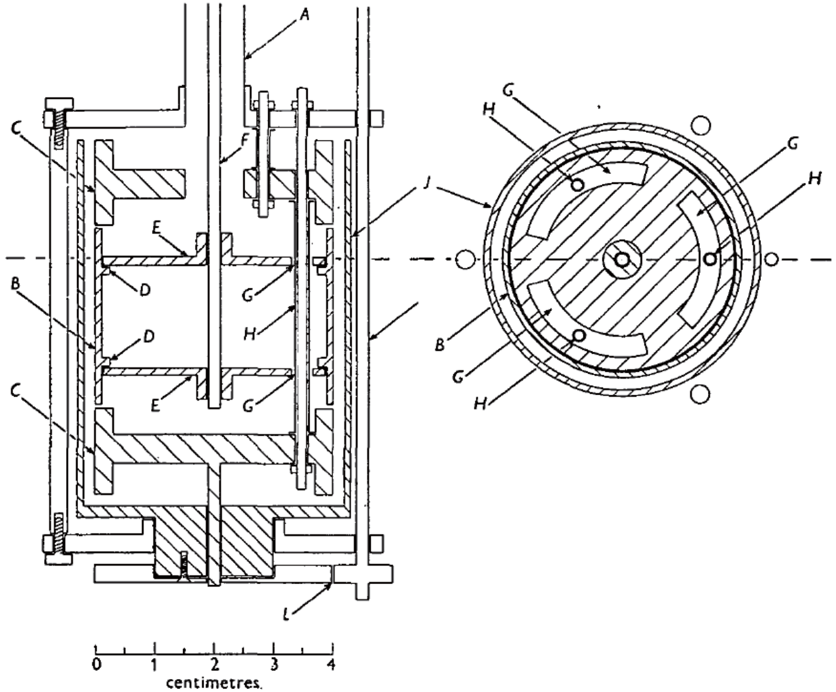
• $v_n \approx 0$, measuring only v_s

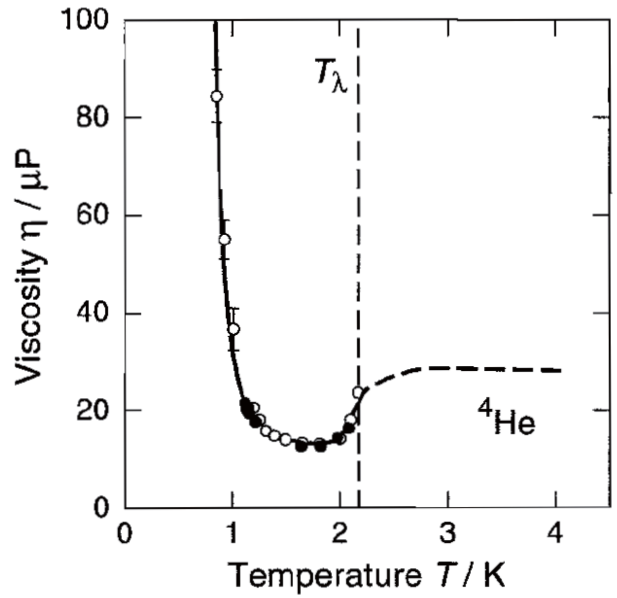
- Can flow without pressure difference (zero viscosity).
- Flow velocity is larger for smaller diameter capillary ($0.1 \le 2r \le 1$ μm).
- Viscosity (η) drops abruptly below T_λ.

2. Rotary viscosimeter exp.

A.D.B. Woods and A.C. Hollis-Hallett, Can. J. Phys. **41**, 596 (1963)
A.C. Hollis-Hallett, Proc. Cambridge Phil. Soc., **49**, 717 (1953)







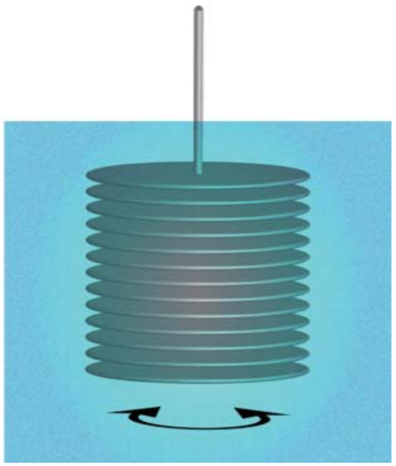
torque on inner cylinder : $M = \dfrac{4\pi r_1^2 r_0^2 h}{\left(r_1^2 - r_0^2\right)} \omega\eta$

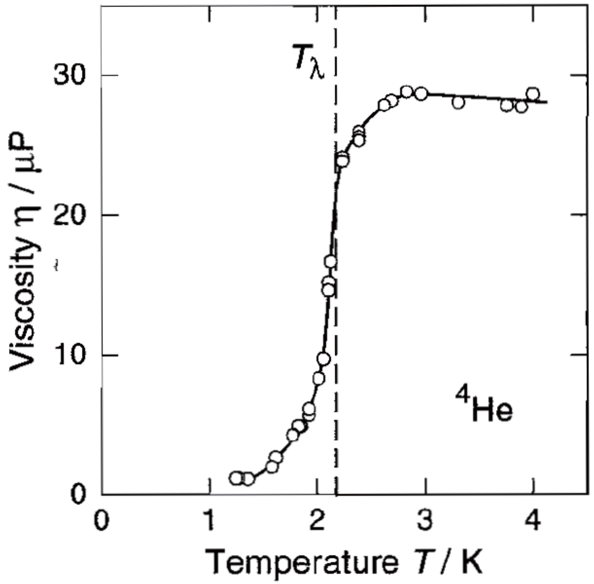
• measuring $\eta = \eta_n$ ($\propto l$)
l: mean free path

- Measure torque on inner cylinder when outer cylinder rotates.
- Apparent viscosity (η) drops below T_λ, but not to zero.
- η increases quickly at $T < 1$ K.

3. Oscillating disc exp.

A. De Troyer et al., Physica **17**, 50 (1951)





rotational torque:

$$M = \pi\sqrt{\rho\eta}\,\omega^{3/2} r^4 \theta_0 \cos(\omega t - \pi/4)$$

• measuring $\rho\eta$ $(= \rho_n \eta_n \propto \rho_n)$

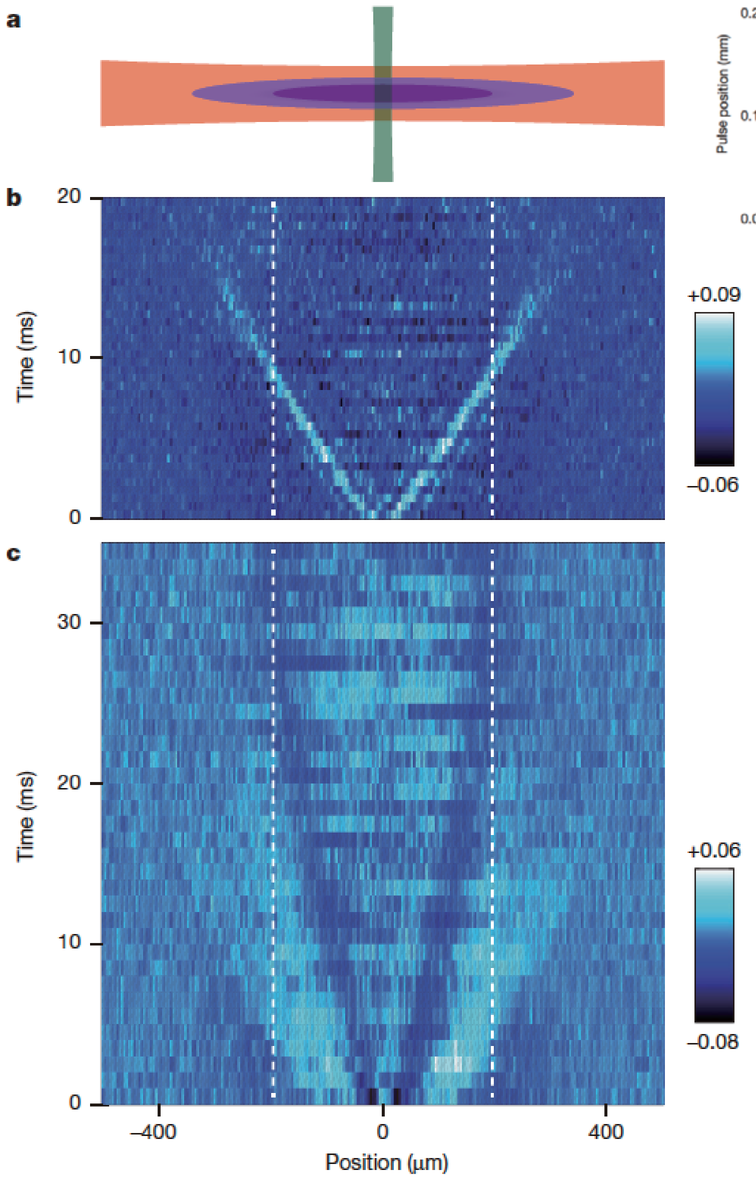
Different methods gave different results, which introduced lots of confusions.

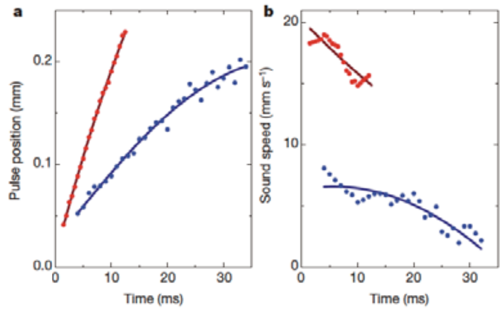
The **two-fluid model** solved the confusion: the different methods detect different quantities.

- Measure torque to oscillate discs with a constant amplitude in He-II.
- Deduced viscosity (η) starts to drop gradually below T_λ and approaches zero as $T \to 0$.

2nd sound in ultra cold Fermi gas

L. A. Sidorenkov, *et al*. Nature **498**, 78 (2013)





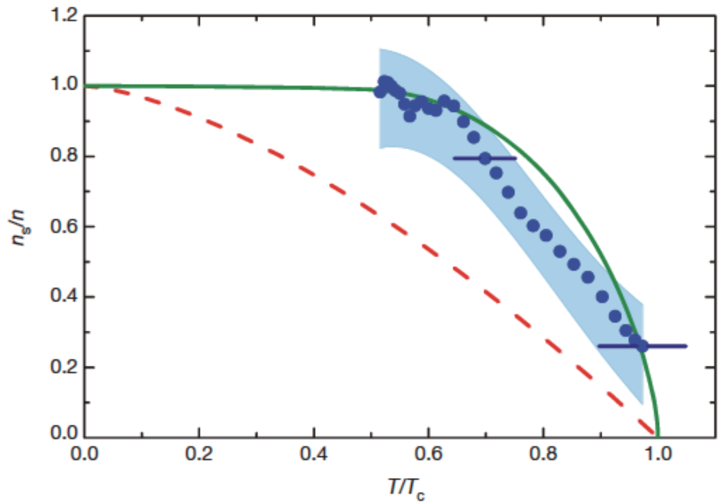


Figure 4 | Superfluid fraction for the homogeneous case. The data points and the corresponding uncertainty range (shaded region) show the superfluid fraction for a uniform, resonantly interacting Fermi gas, reconstructed from its 1D counterpart in Fig. 3b (Methods), as a function of T/T_c. The two horizontal error bars indicate the systematic uncertainties resulting from the limited knowledge of the critical temperature T_c. For comparison, we show the fraction for helium II[26] (solid line) and the textbook expression $1-(T/T_c)^{3/2}$ for the Bose–Einstein condensed fraction of the ideal Bose gas (dashed line).

Figure 1 | Observing the propagation of first and second sound. a, The basic geometry of exciting the optically trapped cloud with a weak, power-modulated repulsive laser beam (green), which perpendicularly intersects the trapping beam (red). The trapped cloud has a superfluid core ($|z| < 190$ μm), surrounded by a normal region (about 1.5 times larger). **b**, **c**, Normalized differential axial density profiles, $\delta n_1(z, t)/n_{1,\max}$ (colour scale), measured for variable delay times after the excitation show the propagation of first sound (local density increase, bright) and second sound (local decrease, dark). The temperature of the atomic cloud is $T = 0.135(10)T_F^{\text{trap}}$. The vertical dashed lines indicate the axial region where superfluid is expected to exist according to a recent determination of the critical temperature[18].